Search for microscopic black hole signatures at the Large Hadron Collider

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A R T I C L E   I N F O

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A B S T R A C T

A search for microscopic black hole production and decay in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 pb⁻¹. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons, typical of a signal expected from a microscopic black hole. Good agreement with the standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV. These are the first direct limits on black hole production at a particle accelerator.

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One of the exciting predictions of theoretical models with extra spatial dimensions and low-scale quantum gravity is the possibility of copious production of microscopic black holes in particle collisions at the CERN Large Hadron Collider (LHC) [1,2]. Models with low-scale gravity are aimed at solving the hierarchy problem, the puzzlingly large difference between the electroweak and Planck scales.

In this Letter we focus on microscopic black hole production in a model with large, flat, extra spatial dimensions, proposed by Arkani-Hamed, Dimopoulos, and Dvali, and referred to as the ADD model [3,4]. This model alleviates the hierarchy problem by introducing n extra dimensions in space, compactified on an n-dimensional torus or sphere with radius r. The multidimensional space–time is only open to the gravitational interaction, while the r-dimensional torus or sphere with radius r

is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV. These are the first direct limits on black hole production at a particle accelerator.

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Once produced, the microscopic black holes would decay thermally via Hawking radiation [12], approximately democratically (with equal probabilities) to all standard model (SM) degrees of

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freedom. Quarks and gluons are the dominant particles produced in the black hole evaporation (∼75%) because they have a large number of color degrees of freedom. The remaining fraction is accounted for by leptons, W and Z bosons, photons, and possibly Higgs bosons. Emission of gravitons by a black hole in the bulk space is generally expected to be suppressed [13], although in some models it can be enhanced for rotating black holes for the case of large \( n \) [10,11,14]. In some models the evaporation is terminated earlier, when the black hole mass reaches \( M_D \), with the formation of a stable non-interacting and non-accreting remnant [15]. The Hawking temperature for a black hole in 4 + \( n \) space–time is given by [1,2,7,8]:
\[
T_{\text{H}} = \frac{1}{16\pi r_{\text{S}}} \text{(in Planck units \( h = c = k_B = 1 \), where \( k_B \) is the Boltzmann constant) and is typically in the range of a few hundred GeV. The lifetime for such a microscopic black hole is \( \sim 10^{-27} \text{ s} \) [1,2,8].
\]

Here we consider semi-classical black holes, whose properties are similar to those for classical black holes described by general relativity and whose mass is close enough to \( M_D \), although the description of rotating black holes in the existing approximations, which is strictly valid only for \( n \ll 1 \), be contrasted with the interaction vertex to suppress backgrounds from cosmic ray muons, be isolated from other tracks, and have transverse momentum \( p_T \) above 20 GeV. The combined fit using tracks measured in the central tracker and the muon spectrometer results in \( p_T \) resolution between 1% and 5% for \( p_T \) values up to 1 TeV.

The separation between any two objects (jet, lepton, or photon) is required to be
\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} > 0.3.
\]

Black hole signal events are simulated using the parton-level BlackMax [27] generator (v2.01.03), followed by a parton-showering fragmentation with PYTHIA [28] (v6.420), and a fast parametric simulation of the CMS detector response [29], which has been extensively validated for signal events using detailed detector simulation via GEANT4 [30].

Several parameters govern black hole production and decay in the ADD model in addition to \( M_D \) and \( n \). For each value of \( M_D \), and for \( n \), we consider a range of the minimum black hole masses, \( M_{\text{BH}}^\text{min} \), between \( M_D \) and the kinematic limit of the LHC. We assume that no parton-collision energy is lost in gravitational shock waves, i.e. it is all trapped within the event horizon of the forming black hole. We consider both rotating and non-rotating black holes in this analysis, although the description of rotating black holes in the existing MC generators is only approximate. Graviton radiation by the black hole is not considered. For most of the signal samples we assume full Hawking evaporation without a stable non-interacting remnant.

The parameters used in the simulations are listed in Table 1 for a number of characteristic model points. The MSTW2008lo68 [31] parton distribution functions (PDF) were used. In addition we compare the BlackMax results with those of the CHARYBDIS 2 MC
n black hole decays. Further, the missing transverse energy in the jets due to pile-up, while being fully efficient for black holes result in events with half-a-dozen objects in the final state. Hence, the signal contribution to the ST distribution to the range

The main background to black hole signals arises from QCD multijet events. Other backgrounds from direct photon, $W/Z$+jets, and $t\bar{t}$ production were estimated from MC simulations, using the MadGRAPH [34] leading-order parton-level event generator with CTEQ6L PDF set [35]; followed by PYTHIA [28] parton showering and full CMS detector simulation via GEANT4 [30]. These additional backgrounds are negligible at large values of $S_T$ and contribute less than 1% to the total background after the final selection.

The dominant multijet background can only be estimated reliably from data. For QCD events, $S_T$ is almost completely determined by the hard $2 \rightarrow 2$ parton scattering process. Further splitting of the jets due to final-state radiation, as well as additional jets due to initial-state radiation – most often nearly collinear with either incoming or outgoing partons – does not change the $S_T$ value considerably. Consequently, the shape of the $S_T$ distribution is expected to be independent of the event multiplicity $N$, as long as $S_T$ is sufficiently above the turn-on region (i.e., much higher than $N \times 50 \text{ GeV}$). This shape invariance offers a direct way of extracting the expected number of background events in the search for black hole production.

We confirmed the assumption of the $S_T$ shape invariance of $N$ up to high multiplicities using MC generators capable of simulating multijet final states from either matrix elements [36] or parton showers [28]. The conjecture that the $S_T$ shape is independent of the multiplicity has been also checked with data using the exclusive multiplicities of $N = 2$ and $N = 3$. Even in the presence of a black hole signal with a mass of a few TeV, the decays of these black holes result in events with half-a-dozen objects in the final state. Hence, the signal contribution to the $N = 2$ and $N = 3$ data is expected to be small and only seen at large values of $S_T$, so these samples still can be used for the background prediction at higher multiplicities. Moreover, since dedicated analyses of the dijet invariant mass spectrum have been conducted [19,20], we know that there are no appreciable contributions from new physics to the dijet final state up to invariant masses of about 1.5 TeV, which, for central jets, translates to a similar range of $S_T$.

We fit the $S_T$ distributions between 600 and 1100 GeV, where no black hole signal is expected, for data events with $N = 2$ and $N = 3$ using an ansatz function $\frac{P_0}{(P_1 + P_2 + x + y)^2}$, which is shown with the solid line in Fig. 1. To check the systematic uncertainty of the fit, we use two additional ansatz functions, $\frac{P_0}{(P_1 + x + y)^2}$ and $\frac{P_0}{(P_1 + P_2 + x + y)^2}$ [19], which are shown as the upper and lower boundaries of the shaded band in Fig. 1. The default choice of the ansatz function was made based on the best-fit to the $S_T$ distribution for $N = 2$. Additional systematic uncertainty arises from a slight difference between the best-fit shapes for $N = 2$ and $N = 3$. Nevertheless, the fits for these two exclusive multiplicities agree with each other within the uncertainties, demonstrating that the shape of the $S_T$ distribution is independent of the final-state multiplicity.

The $S_T$ distributions for data events with multiplicities $N \geq 3$, 4, and 5 are shown in Figs. 2a, b, and c, respectively. The solid curves in the figures are the predicted background shapes, found by normalizing the fits of the $N = 2$ $S_T$ distribution to the range.

### Table 1

Monte Carlo signal points for some of the model parameters probed, corresponding leading order cross sections ($\sigma$), and the minimum required values for the event multiplicity ($N \geq N_{\text{min}}$) and $S_T$ ($S_T > S_{T\text{min}}$), as well as the signal acceptance ($A$), the expected number of signal events ($n_{\text{sig}}$), and the observed ($n_{\text{obs}}$) and expected ($\sigma_{\text{obs}}$) limits on the signal cross section at 95% confidence level.

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<th>$M_0$ (TeV)</th>
<th>$M_{\text{min}}^\text{SM}$ (TeV)</th>
<th>$n$</th>
<th>$\sigma$ (pb)</th>
<th>$N_{\text{min}}$</th>
<th>$S_{T\text{min}}$ (TeV)</th>
<th>$A$ (%)</th>
<th>$n_{\text{sig}}$</th>
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<tr>
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<td>0</td>
<td>0.03 ± 0.03</td>
</tr>
</tbody>
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Fig. 1. Total transverse energy $S_T$, for events with the multiplicities of a) $N = 2$, and b) $N = 3$ objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

Fig. 2. Total transverse energy $S_T$, for events with multiplicities a) $N \geq 3$, b) $N \geq 4$, and c) $N \geq 5$ objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction (solid line) with its uncertainty. Also shown are black hole signals for three different parameter sets.

$S_T = 1000$–$1100$ GeV, where no black hole signal contribution is expected.

Since no excess is observed above the predicted background, we set limits on the black hole production. We assign a systematic uncertainty on the background estimate of 6% to 125% for the $S_T$ range used in this search. This uncertainty comes from the normalization uncertainty (4–12%, dominated by the statistics in the normalization region) added in quadrature to the uncertainties arising from using various ansatz fit functions and the difference between the shapes obtained from the $N = 2$ and $N = 3$ samples. The integrated luminosity is measured with an uncertainty of 11% [22]. The uncertainty on the signal yield is dominated by the jet-energy-scale uncertainty of $\approx 5\%$ [24] which translates into a 5% uncertainty on the signal. An additional 2% uncertainty on
the signal acceptance comes from the variation of PDFs within the CTEQ6 error set [35]. The particle identification efficiency does not affect the signal distribution, since an electron failing the identification requirements would be classified either as a photon or a jet; a photon failing the selection would become a jet; a rejected muon would contribute to the $E_T$. In any case the total value of $S_T$ is not affected.

We set limits on black hole production with the optimized $S_T$ and $N$ selections by counting events with $S_T > S_T^{\text{min}}$ and $N > N^{\text{min}}$. We optimized the signal ($S$) significance in the presence of background ($B$) using the ratio $S/\sqrt{S+B}$ for each set. The optimum choice of parameters is listed in Table 1, as well as the predicted number of background events, the expected number of signal events, and the observed number of events in data. Note that the background uncertainty, dominated by the choice of the fitting function, is highly correlated for various working points listed in Table 1 and also bin-to-bin for the $S_T$ distributions shown in Figs. 1 and 2.

We set upper limits on the black hole production cross section using the Bayesian method with flat signal prior and log-normal prior for integration over the nuisance parameters (background, signal acceptance, luminosity) [5,37]. These upper limits at the 95% confidence level (CL) are shown in Fig. 3, as a function of $M_{\text{BH}}^{\text{min}}$. For the three model parameter sets shown in the figure, the observed (expected) lower limits on the black hole mass are 3.5, 4.2 and 4.5 TeV (3.2, 4.0, and 4.5 TeV), respectively.

Translating these upper limits into lower limits on the parameters of the ADD model, we can exclude the production of black holes with minimum mass of 3.5–4.5 TeV for values of the multidimensional Planck scale up to 3.5 TeV at 95% CL. These limits, shown in Fig. 4, do not exhibit significant dependence on the details of the production and evaporation within the set of models we studied. These are the first limits of a dedicated search for black hole production at a particle accelerator.

We point out that the semi-classical approximation used in this search is valid only for the lowest values of the $M_B$, for which the limits on the minimum black hole mass exceed $M_B$ by a factor of a few. For higher values of $M_B$ the limits become comparable with $M_B$, which implies that the approximation is no longer valid and that the BH production cross section may be modified significantly. Nevertheless, due to the exponentially falling nature of production cross section with the black hole mass, even large changes in the cross section translate only in moderate changes in the minimum black hole mass limit, as evident from Fig. 3.

Finally, we produce model-independent upper limits on the cross section times the acceptance for new physics production in high-$S_T$ inclusive final states for $N \geq 3$, 4, and 5. Fig. 5 shows 95% CL upper limits from a counting experiment for $S_T > S_T^{\text{min}}$ as a function of $S_T^{\text{min}}$, which can be used to test models of new physics that result in these final states. A few examples of such models are production of high-mass $t\bar{t}$ resonances [38] in the six-jet and lepton + jet final states, $R$-parity violating gluino decay into three jets, resulting in the six-jet final state [39,40], and a class of models with strong dynamics, with a strongly produced resonance decaying into a pair of resonances further decaying into two jets each, resulting in the four-jet final state [41]. In addition, these limits can be used to constrain black hole production for additional regions of the parameter space of the model, as well as set limits on the existence of string balls [42], which are quantum precursors of black holes predicted in certain string models. We have checked that for the black hole model parameters we probed with the dedicated optimized analysis, the sensitivity of the search in terms of the excluded black hole mass range exceeds that from the model-independent cross section limits by as little as 5–8%. Thus, model-independent limits can be used efficiently to constrain the allowed parameter space in an even broader variety of black hole models than we covered in this Letter.

To conclude, we have performed the first dedicated search for microscopic black holes at a particle accelerator and set limits on their production in the model with large extra dimensions in space using simple semi-classical approximation of the black hole production and decay [1,2]. The lower limits on the black hole mass at 95% CL range from 3.5 to 4.5 TeV for values of the Planck scale up to 3 TeV. Additionally, we have produced model-independent limits on the production of energetic, high-multiplicity final states, which can be used to constrain a variety of models of new physics.

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Fig. 5. Model-independent 95% confidence level upper limits on a signal cross section times acceptance for counting experiments with $S_T > S_T^{min}$ as a function of $S_T^{min}$ for (a) $N \geq 3$, (b) $N \geq 4$, and (c) $N \geq 5$. The solid (dashed) lines correspond to observed (expected) upper limits for nominal signal acceptance uncertainty of 5%.

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